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RESEARCH DEPARTMENT REPORT

STEREOPHONIC RECEPTION USING THE PILOT-TONE SYSTEM: compatibility of current receivers when quadrature subcarrier modulation is added

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STEREOPHONIC RECEPTION USING THE PILOT-TONE SYSTEM: COMPATIBILITY OF CURRENT RECEIVERS WHEN QUADRATURE SUBCARRIER MODULATION IS ADDED

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Summary

This Report describes the results of measurements made on ten current stereo receivers to determine the effect on stereo reception when a pair of sidebands are added in quadrature to those of the existing difference signal, centred on 38 kHz. The measurements were mainly objective but the results of a brief listening test are also described.

The effect, which is more marked with some receivers than with others, is to cause a shift of the stereo image to the left or right and, to an extent which is less objectionable subjectively, to increase the levels of second- and third-harmonic distortion.

It is believed that the shift of the stereo image could be overcome at little extra cost in future-generation stereo decoders, but to reduce the level of distortion may require significant change to the design of particular decoders.

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1. Introduction

If future UK requirements for quadraphony cannot be met by matrix systems using two audio channels,[1] it will be necessary to consider methods by which at least one further channel may be added to the present pilot-tone system for stereophony. This further information would be added in such a way, of course, as to cause minimal impairment to reception and reproduction for both mono and stereo listeners.

The form that such quadraphonic information should take, and the manner by which it should be transmitted, is currently being studied.[2] It is likely that, if such information is needed, it would be transmitted, at least in part, in the form of double-sideband suppressed-carrier amplitude modulation, the two sidebands of which are centred on 38 kHz but in quadrature with those of the difference signal of the present pilot-tone stereo system.[2,3]

The addition of such sidebands would not affect monophonic listeners but it may impair reproduction for stereo listeners. This report describes tests that were carried out on ten current models of stereo receiver in order to assess the nature and the degree of the impairment that would be caused.

2. Theoretical considerations

The output signals from a perfect stereo decoder would not be affected by the presence of the quadrature sidebands. A decoder departs from the ideal, however, if the 38 kHz subcarrier is regenerated within it either with insufficient amplitude or in an incorrect phase (relative to that of the 19 kHz pilot tone).

As shown in the Appendix, quite a large phase error is permissible for normal stereophonic reception but, if further sidebands are added in quadrature to those of the stereo difference signal, the effect of the phase error is to cause a proportion of their modulation to be added to the output signal from one channel of a stereo receiver, and to be subtracted from the output signal from the other. The result depends upon the nature of the modulation carried by the quadrature sidebands but, if it contains components common to the baseband (sum) signal, it causes a shift of the acoustic image, to the left or the right, for the stereo listener. Fig. 1 shows the shift calculated (from the results of earlier work[4]) as a function of subcarrier phase error, that would be caused to a central stereo image if the modulation carried by the quadrature sidebands were the same as that carried by the M (or sum) signal. This is perhaps the extreme case but, since shifts of about ·05 stage-width are found to be perceptible,[4] it is evident that such a modulation condition would impose a tolerance of ±5° on the phase of the regenerated 38 kHz subcarrier. As will be shown in Section 3, phase errors in excess of that tolerance were found to be present in six of the ten receivers tested.

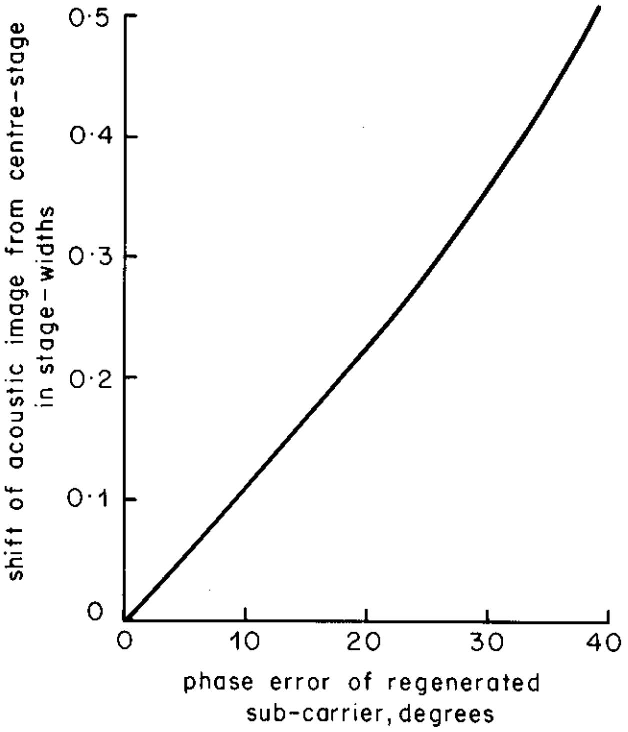

Fig. 1 - Shift of acoustic image caused by incorrect phase of regenerated 38 kHz subcarrier

As also shown in the Appendix, even-order harmonics of the quadrature-sideband modulation occur in antiphase at the two output channels from the decoder, even if the phase of the regenerated 38 kHz subcarrier is correct. If the phase of the regenerated subcarrier is incorrect, odd-order harmonics also occur (in antiphase) at the two outputs. The relative level of these harmonics depends upon both the type of decoder and the level of the subcarrier regenerated within it but, in general, all decoders would require a much larger subcarrier (for a given harmonic level) in the presence of quadrature sidebands than for normal stereo signals. It is shown in the Appendix that in order to reduce the relative level of second harmonic to 1% from a sum-and-difference-separation decoder with envelope detector, when it is dealing with quadrature sidebands modulated in the manner described in the preceding paragraph, would require the amplitude of the regenerated subcarrier at the detector to be at least 50 times that of each of the quadrature sidebands. This result cannot be applied directly to switching decoders or those using multiplicative (or syn-

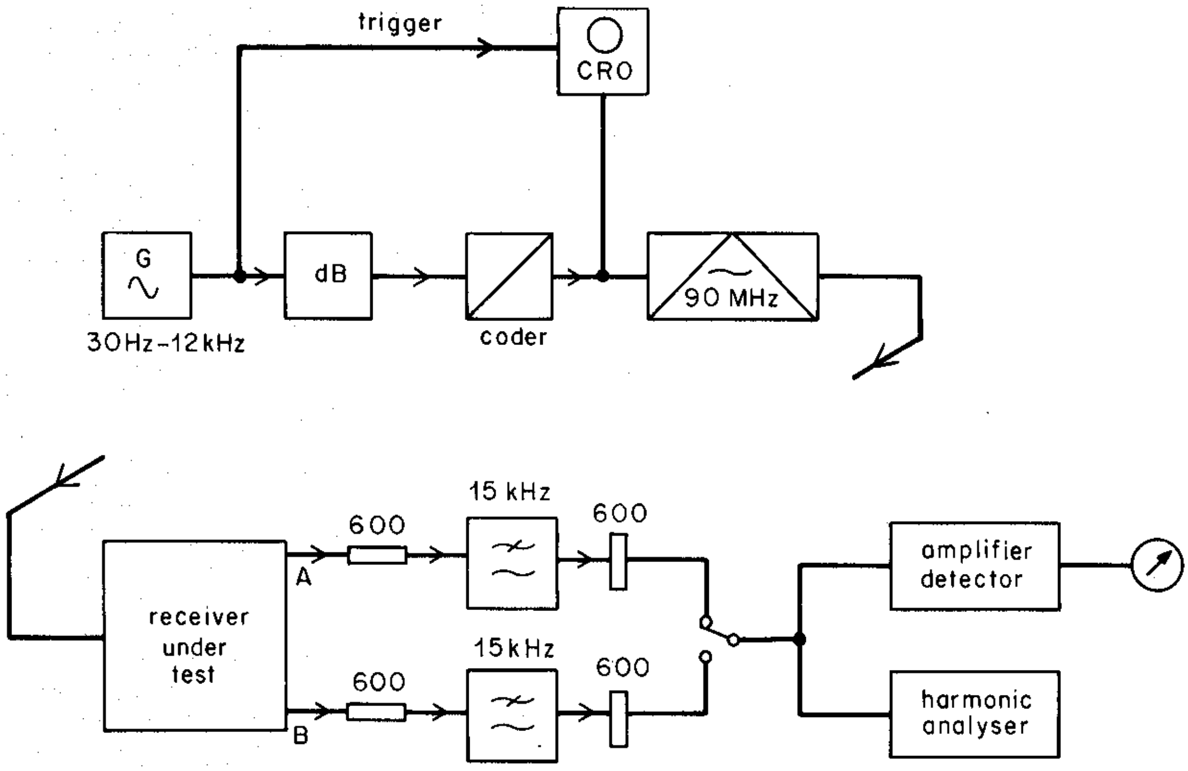

Fig. 2 - Arrangement of equipment for objective measurements

chronous) detectors but it serves to illustrate how closely the switches or multipliers in such decoders must approximate to the ideal.

3. Method of test

3.1. General

Tests were performed on ten current models of stereo receivers, eight of which were loaned for the purpose, by arrangement with BREMA,* by three UK manufacturers. All the receivers were tested objectively and, as a result, four particular receivers were selected for brief subjective assessments.

3.2. Objective measurements

3.2.1. Choice of test signals

For the objective measurements the arrangement shown block-schematically in Fig. 2 was used. The multiplex test signal adopted is defined in the Appendix. Its waveform (before adding the 19 kHz pilot tone) is shown in Fig. 3. It comprises a sinusoidal M signal together with an equal-amplitude sinusoidal S signal the two sidebands of which could be switched in the coder so as to be either in phase or in quadrature with the 19 kHz pilot tone. This test signal was chosen because it enables the levels of cross-talk between channels, and the harmonic content of the output from each channel, to be measured with similar signal levels in both the sum and the difference channel of each receiver in both the in-phase and the quadrature condition.

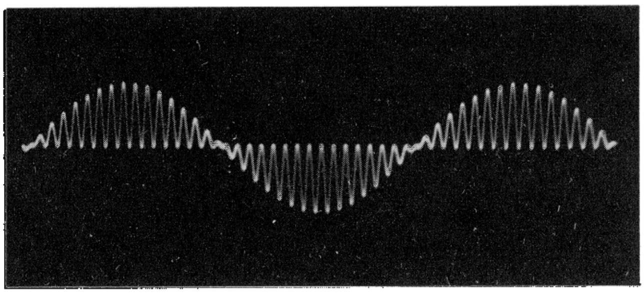

Fig. 3 - Multiplex waveform used for objective measurements

3.2.2. Crosstalk between channels

If the receiver decoder were perfect, there would be an output from only its left-hand channel when using the test signal in the in-phase condition. In the quadrature condition the outputs from both channels would be equal and 6 dB less than the left-hand channel output for the in-phase condition. If the 38 kHz subcarrier is regenerated in the decoder with incorrect phase, however, cross-talk occurs from the quadrature sidebands into the two channels, causing the signal levels in the two channels to become unequal (see Section 2). The ratio of their levels provides an indication of the shift of the acoustic image to the left or right that the presence of the quadrature sidebands could cause to a stereo listener. The effect is shown in Fig. 4,

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* British Radio Equipment Manufacturers' Association.

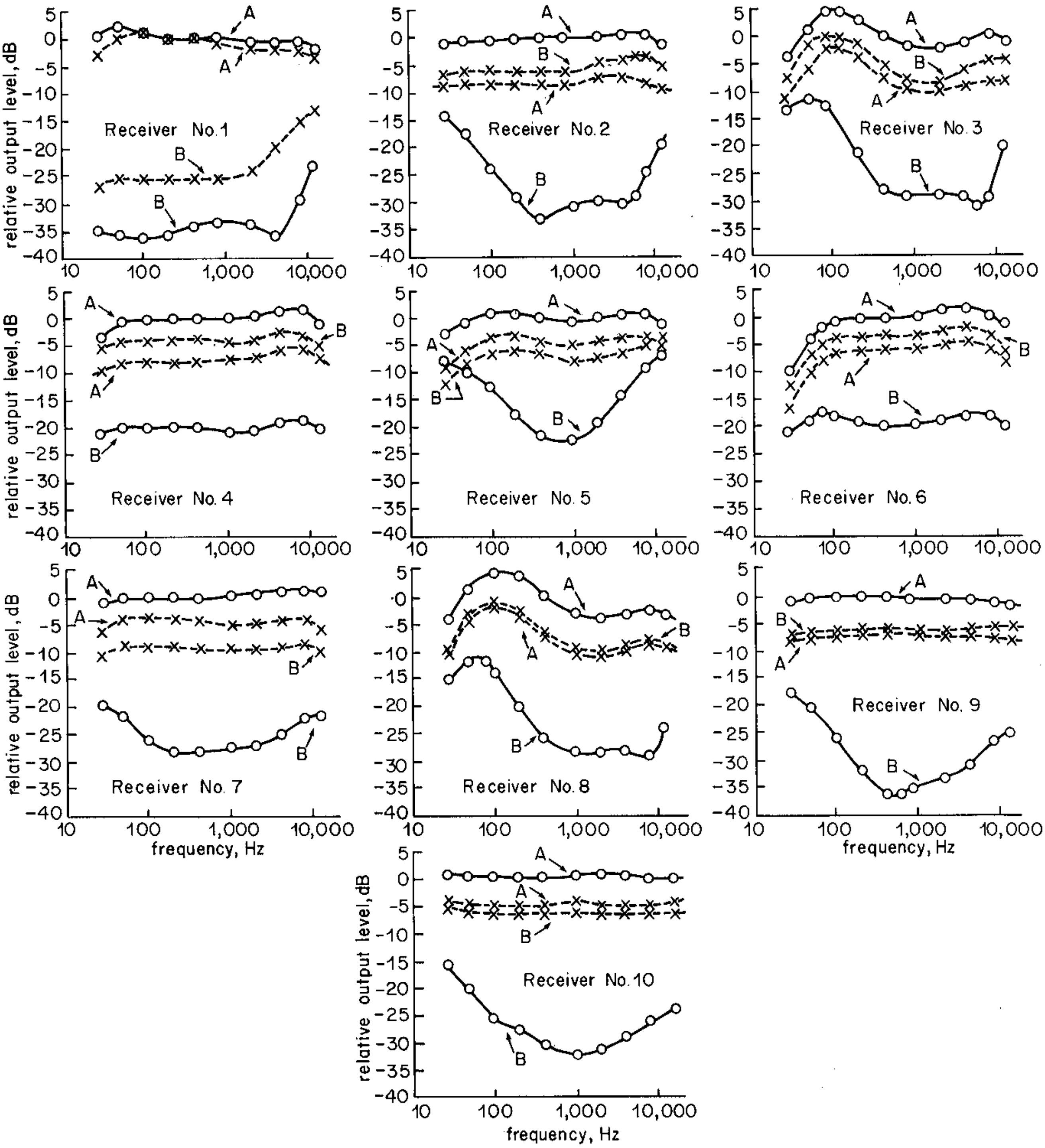

Fig. 4 - Receiver output levels with in-phase and quadrature subcarrier sidebands (corrected for 50 µs pre-emphasis)

o—o—o sidebands in phase —x—x—x— sidebands in quadrature

which shows the measured output levels from the two channels of each receiver, as a function of modulation frequency, for both the in-phase and the quadrature conditions.

The effect, which varies widely between receivers, is summarised in Table 1. It is shown in the Appendix that, if θ is the phase error of the regenerated subcarrier, the amplitudes of the two output signals from the decoder would be expected to be in the ratio $(1 + \tan\theta)/(1 - \tan\theta)$. Accordingly, the value of $\theta/2$ for each receiver was measured by determining the amount by which the phase of the 19 kHz pilot tone needed to be changed in order to minimise the output from either channel when using a multiplex signal that comprised only a pair of quadrature sidebands plus the 19 kHz pilot tone. Those results, together with the ratios $(1 + \tan\theta)/(1 - \tan\theta)$, are included in Table 1.

TABLE 1

Cross-talk between channels at 400 Hz modulation frequency

Receiver No.	Measured value of θ, degrees	Amplitude ratio, A and B channel signals:—	
		$(1 + \tan\theta)/(1 - \tan\theta)$	Measured at 400 Hz (see Fig. 4)
1	40·8	22·7 dB	26·2 dB
2	10·0	3·1 dB	1·6 dB
3	6·8	2·1 dB	1·2 dB
4	15·0	4·8 dB	4·0 dB
5	7·2	2·2 dB	2·2 dB
6	4·2	1·3 dB	1·6 dB
7	6·8	2·1 dB	4·0 dB
8	1·0	0·3 dB	0·2 dB
9	1·2	0·4 dB	0·8 dB
10	1·8	0·5 dB	0·8 dB

3.2.3. Harmonic content

If the 38 kHz subcarrier is regenerated within the decoder with insufficient amplitude, harmonics and intermodulation products of the quadrature-sideband modulation occur (in antiphase) at its two outputs. The harmonic levels from each receiver, measured as a function of modulation depth when using the test signals described in Section 3.2.1. at a modulation frequency of 400 Hz, are shown in Fig. 5.

3.3. Subjective tests

In order to assess the degree of subjective impairment that is associated with the objective results shown in Figs. 4 and 5, brief subjective tests were made using receivers Nos. 1, 6, 9 and 10. The receiver outputs were fed to a pair of high-grade loudspeakers arranged in a listening room; passages of both speech and music were used for the modulation. The coder was arranged to modulate the programme onto the carrier as an M signal only, thus producing equal in-phase outputs from the two loudspeakers and causing a sharply-defined central acoustic image. In addition, the listener was provided with a switch by which the programme could also be applied with equal amplitude, when required, to the quadrature-sideband modulator of the coder so as to introduce a pair of quadrature sidebands whose combined amplitude was equal to that of the M signal. The modulation condition was then analogous to that for stereophony in which there are equal M and S signals (i.e. zero signal in either the left or right channel) but with the S-signal sidebands in quadrature. The receiver outputs should, ideally, have been completely unaffected by the introduction of these quadrature sidebands but, as would be expected from the objective results shown in Figs. 4 and 5, their introduction caused a shift of the acoustic image to the left or right and it was accompanied, to an extent which depended upon the choice of receiver, by the introduction of harmonic distortion.

The shift of the acoustic image was found to accord with the results of Fig. 4 (and Table 1), taken in conjunction with the curve of Fig. 1. It was also found that the presence of more than about 5% or 6% second-harmonic or third-harmonic distortion caused noticeable impairment, notably because, as shown in the Appendix, it was reproduced in antiphase from the two loudspeakers. As shown in Fig. 5, three of the ten receivers tested caused harmonic distortion in excess of that figure.

4. Conclusions

The introduction, for quadraphony, of a further pair of sidebands, centred on 38 kHz but in quadrature with those forming the difference signal of the present pilot-tone stereo system, would not affect monophonic listeners but, on the basis of the tests described on ten current models of stereo receiver, it may impair reproduction for stereo listeners. The dominant impairment is a shift of the acoustic image to the left or right and, to a lesser extent, the occurrence of harmonic distortion at a level which is objectionable mainly because it is reproduced in antiphase from the two loudspeakers.

The proportion of stereo listeners that would be affected in this way cannot be predicted until the nature of the modulation that would be applied to the quadrature

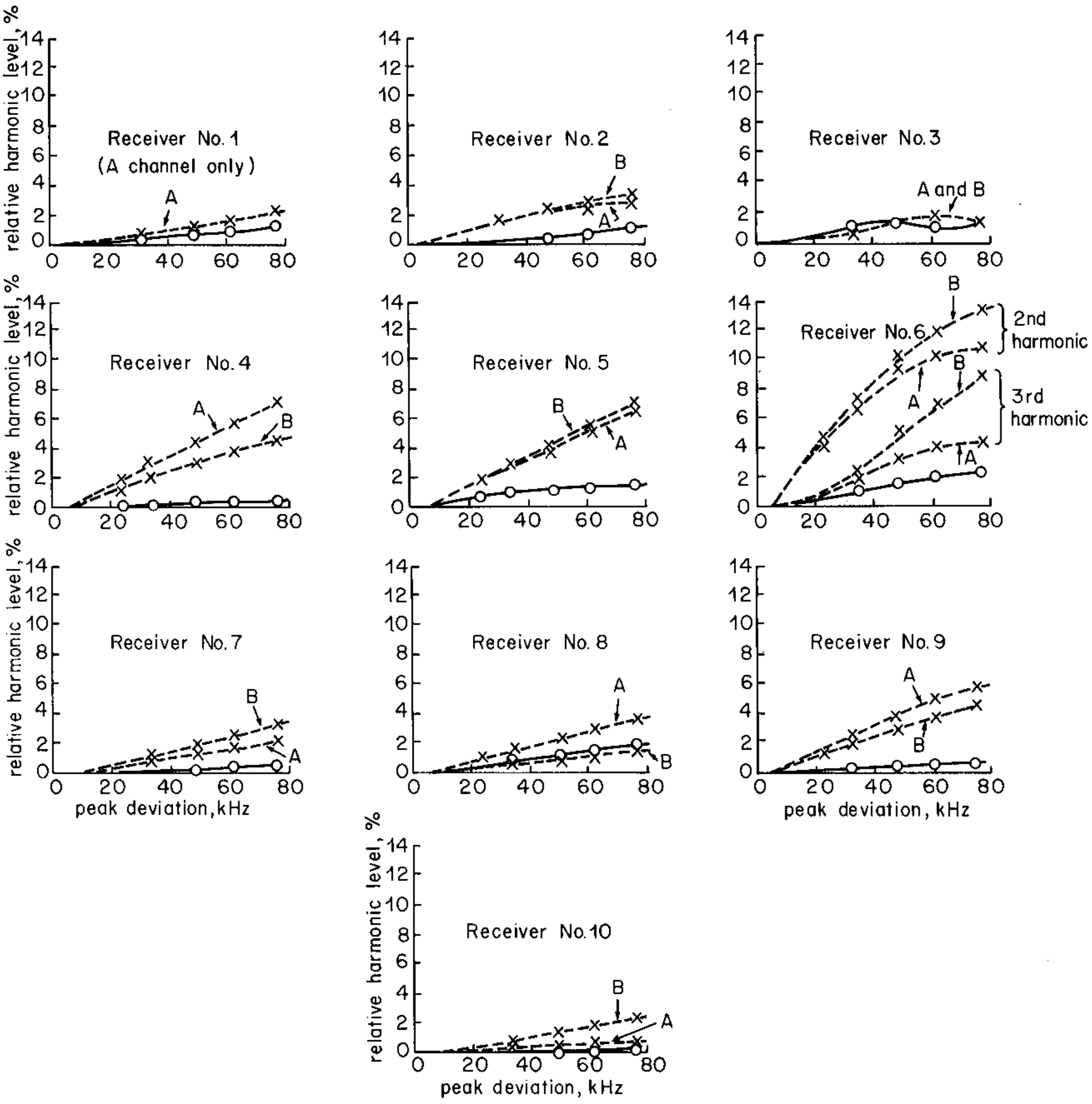

Fig. 5 - Harmonic content with in-phase and quadrature subcarrier sidebands

—o——o——o— sidebands in phase, A channel only —x— —x— —x— sidebands in quadrature, A and B channels

sidebands is known but the modulation condition adopted for the tests described, which perhaps represented the worst case, caused noticeable shift of acoustic image when reproduced from six of the ten receivers tested, and noticeable harmonic distortion from three of them.

In order to avoid such impairments, receiver decoders require more careful alignment and a more nearly perfect demodulating or switching action then is required for normal stereophony. The pilot-tone alignment could perhaps be sufficiently improved in future receivers with little extra cost if the need for it were made known to manufacturers, but significant extra cost may be involved for certain decoders in suitably improving their demodulating or switching action in order to remove harmonic distortion.

5. References

1. CROMPTON, T.W.J. The subjective performance of various quadraphonic matrix systems. BBC Research Department Report No. 1974/29.
2. TINGLEY, E.M. The National Quadraphonic Radio Committee (N.Q.R.C.). International Broadcasting Convention, London, 1974, I.E.E. Conference Publication No. 119, p. 21.
3. NETZBAND, R. Multiplex systems for VHF/FM sound broadcasting. EBU Review, No. 147, October 1974, pp. 225 – 229.
4. HARWOOD, H.D. Stereophonic image sharpness. *Wireless World*, **74**, 1393, July 1968, pp. 207 – 211.

6. Appendix: Cross-talk and distortion as a function of amplitude and phase of regenerated subcarrier

6.1. Definitions

The instantaneous deviation of an f.m. transmitter transmitting the pilot-tone stereo system may be expressed, as a fraction of 75 kHz, as:–

$$D = 0{\cdot}9[M + S \sin \omega t + 0{\cdot}1 \sin \omega t/2] \qquad (1)$$

where $M = (A + B)/2$
$S = (A - B)/2$
A and B (which can vary within the range ±1) represent the pre-emphasised signals in the left and right channels

and $\omega/2\pi$ is the subcarrier frequency (38 kHz).

For the objective measurements described in this Report the particular modulation condition chosen was $A = \alpha \sin pt$, $B = 0$, where $p/2\pi$ is the modulation frequency and α may have any value from 0 to 1. Furthermore, the phase of the difference-signal sidebands within the coder could be switched so that the resulting deviation could be either as defined by Equation (1), the 'in-phase' condition, or by:–

$$D_Q = 0{\cdot}9[M + S \cos \omega t + 0{\cdot}1 \sin \omega t/2] \qquad (2)$$

the 'quadrature' condition.

In either condition the multiplex waveform was as shown in Fig. 3.

6.2. The 'in-phase' condition

If the receiver has a sum and difference separation decoder with an envelope detector, the received S signal comprises a pair of sidebands, each of amplitude $h\alpha/4$ (where h is an arbitrary constant), centred on 38 kHz, as represented by OA and OB in Fig. 6(*a*); their resultant is

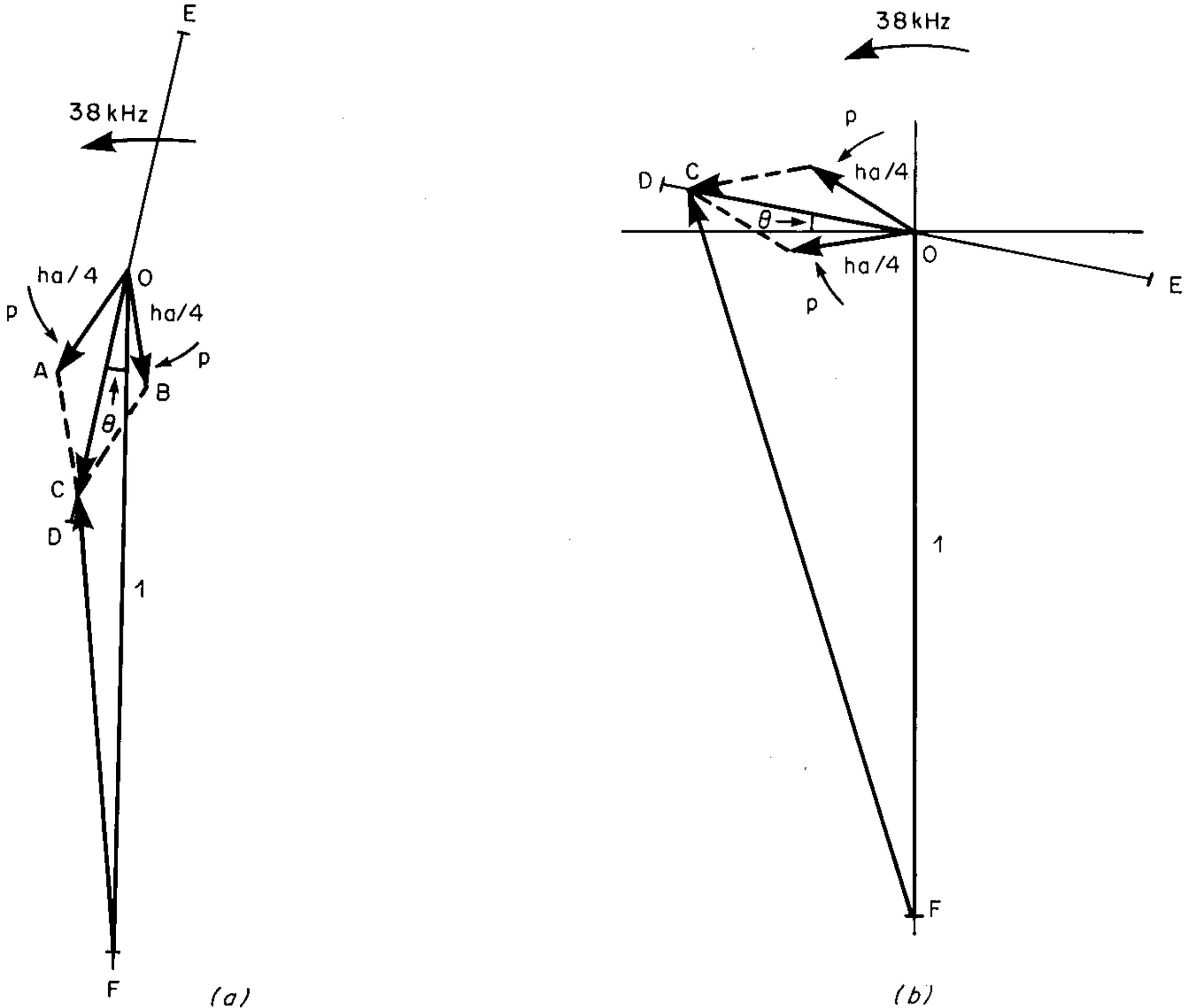

Fig. 6 - Vector relationships in the decoder
(*a*) With sidebands in phase (*b*) With sidebands in quadrature

represented by the vector OC whose amplitude varies along the locus DOE. If the 38 kHz regenerated subcarrier is added with unit amplitude, and phase θ relative to the locus DOE, as shown in Fig. 6(*a*), the envelope of the resultant may be represented by the vector FC, the tip of which travels along the locus DOE and back over one complete modulation cycle. Thus, for that modulation condition, the demodulated S signal is given by:—

$$S' = [1 + h\alpha \sin pt \cos\theta + (1/4)\, h^2\alpha^2 \sin^2 pt]^{1/2} - 1 \qquad (3)$$

If the sidebands are sufficiently small compared to the re-introduced carrier, the demodulated S signal may be expressed as:—

$$\begin{aligned} S' = \; & [(1/2)\, h\alpha \cos\theta + \ldots\ldots\ldots]\, \sin pt \\ & - [(1/16)\, h^2\alpha^2 \sin^2\theta + \ldots\ldots]\, \cos 2pt \\ & + [(1/64)\, h^3\alpha^3 \cos\theta \sin^2\theta + \ldots\ldots]\, \sin 3pt \\ & + \text{terms in higher powers of } h\alpha \qquad (4) \end{aligned}$$

and the outputs from the two channels of the decoder as:—

$$\begin{aligned} A' = M + S' = \; & [(\alpha/2)(1 + h\cos\theta) + \ldots]\, \sin pt \\ & - [(1/16)\, h^2\alpha^2 \sin^2\theta + \ldots]\, \cos 2pt \\ & + [(1/64)\, h^3\alpha^3 \cos\theta \sin^2\theta + \ldots]\, \sin 3pt \qquad (5) \end{aligned}$$

$$\begin{aligned} B' = M - S' = \; & [(\alpha/2)(1 - h\cos\theta) + \ldots]\, \sin pt \\ & + [(1/16)\, h^2\alpha^2 \sin^2\theta + \ldots]\, \cos 2pt \\ & - [(1/64)\, h^3\alpha^3 \cos\theta \sin^2\theta + \ldots]\, \sin 3pt \qquad (6) \end{aligned}$$

For an ideal decoder, h would be unity and θ would be zero but departures from these values are allowed for in a practical decoder when, during its alignment, the crosstalk between channels is minimised and, in effect, the product $h\cos\theta$ is made equal to unity. Under those conditions,

$$\begin{aligned} A' = \; & [\alpha + \ldots]\, \sin pt \\ & - [(1/16)\, \alpha^2 \tan^2\theta + \ldots]\, \cos 2pt \\ & + [(1/64)\, \alpha^3 \tan^2\theta + \ldots]\, \sin 3pt \qquad (7) \\ B' = \; & [(1/16)\, \alpha^2 \tan^2\theta + \ldots]\, \cos 2pt \\ & - [(1/64)\, \alpha^3 \tan^2\theta + \ldots]\, \sin 3pt \qquad (8) \end{aligned}$$

Thus, for normal stereophony, fairly large values of θ are permissible from the point of view of crosstalk, the limit being set instead by signal/noise ratio of the difference signal and by harmonic distortion. Furthermore, the residual harmonic distortion occurs at an acceptable level if the 38 kHz regenerated subcarrier is injected with reasonable level into the demodulator. Values of θ as large as 20°, for example, would cause little more than 1% second-harmonic distortion if the amplitude of the injected subcarrier were only about 3 times that of each difference-signal sideband.

6.3. The 'quadrature' condition

In this condition the vector diagram of Fig. 6(*b*) applies and, by a treatment similar to the above (and again putting $h\cos\theta = 1$) the outputs from the two channels may be shown to be:—

$$\begin{aligned} A'' = \; & [(\alpha/2)(1 - \tan\theta) + \ldots]\, \sin pt \\ & - [(1/16)\, \alpha^2 + \ldots]\, \cos 2pt \\ & - [(1/64)\, \alpha^3 \tan\theta + \ldots]\, \sin 3pt \qquad (9) \\ B'' = \; & [(\alpha/2)(1 + \tan\theta) + \ldots]\, \sin pt \\ & + [(1/16)\, \alpha^2 + \ldots]\, \cos 2pt \\ & + [(1/64)\, \alpha^3 \tan\theta + \ldots]\, \sin 3pt \qquad (10) \end{aligned}$$

Thus, for this modulation condition, the contribution $(\alpha/2)\tan\theta$ from the quadrature sidebands is added to the output from one channel and subtracted from the output from the other. Furthermore, in order to reduce the level of second harmonic distortion to 1%, the amplitude of the injected subcarrier needs to be 50 times larger than that of either of the quadrature sidebands if $\theta = 0$, and larger still if θ has a non-zero value.

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